

Application and Extension of the Particle X-ray Coincidence Technique to Astrophysical Reaction Rates

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Abstract

Lifetimes of excited nuclear states are crucial in many aspects of nuclear physics, from nuclear structure to astrophysics. It has been demonstrated that the particle-X-ray coincidence technique (PXCT) developed based on an atomic clock technique can provide one of the best ways of probing the lifetimes of excited nuclear states in the time range of $10^{-17} - 10^{-15}$ s. We have developed a detection system at the Facilities for Rare Isotope Beams to extend this technique to measure the lifetimes of discrete resonances required for thermonuclear reaction rate calculations. The full power FRIB will yield a rate of 1.2×10^5 per second ^{60}Ga . This work aims to open a path to significantly improved constraints on the strength of the NiCu cycle on the rapid proton capture process by measuring ^{60}Ga decay with the PXCT system.

1. Introduction

In the 1970s, the Particle X-ray Coincidence Technique (PXCT) was initially demonstrated and applied to measure the average lifetimes of proton-unbound states in ^{69}As populated by the electron capture (EC) of ^{69}Se [1]. The principle of the method is illustrated in Fig. 1. In the process of an EC-delayed proton emission, a proton-rich precursor with an atomic number of Z decays by K -EC to the proton emitter ($Z - 1$). Due to the EC, a proton unbound nuclear state and an atomic shell vacancy are created simultaneously. An atomic electron in a higher-lying shell fills the vacancy with typical lifetimes of $\tau_{K\text{shell}} = 0.01$ to 1.0 fs and emits the characteristic X ray. Meanwhile, the proton-unbound state with a comparable lifetime $\tau_{p\text{-emit}}$ emits a proton to a state of the daughter ($Z - 2$). If the proton is emitted before the X-ray emission, then the characteristic X-ray energy will correspond to the atomic number of the daughter ($Z - 2$). If the proton is emitted after the X-ray emission, then the X-ray energy will be characteristic of the atomic number of the proton emitter ($Z - 1$). By measuring the spectrum of X rays in coincidence with protons and counting the relative intensities of the $Z - 1$ and $Z - 2$ X-ray peaks $I_{KX(Z-1)}/I_{KX(Z-2)}$, the lifetimes of proton-emitting states can be related to the lifetimes of the emitter K -shell vacancies by the relation

$$\frac{\tau_{p\text{-emit}}}{\tau_{K\text{shell}}} = \frac{\Gamma_{K\text{shell}}}{\Gamma_{p\text{-emit}}} = \frac{I_{KX(Z-1)}}{I_{KX(Z-2)}}, \quad (1)$$

where the decay width $\Gamma_{K\text{shell}}$ and $\Gamma_{p\text{-emit}}$ is the equivalent of $\hbar/\tau_{K\text{shell}}$ and $\hbar/\tau_{p\text{-emit}}$, respectively, as they both follow the exponential decay law. Because the K -shell vacancy lifetimes are well known both experimentally and theoretically, ranging from $\tau \approx 2 \times 10^{-15}$ s for carbon down to $\tau \approx 6 \times 10^{-18}$ s for uranium [2, 3], lifetimes of proton-emitting states can be established with reasonable accuracy. The preceding discussion is also generalizable to EC-delayed α -particle emission. This ‘atomic clock’ method has been successfully applied to measure the average sub-fs lifetimes of proton-unbound states populated by the ECs of ^{65}Ge [4], ^{69}Se [5, 4], ^{73}Kr [6, 7, 4], ^{77}Sr [4], ^{113}Xe [8], and ^{117}Ba [9].

In all the aforementioned cases, excited states could not be distinguished individually as their level density was too high, and none of the measured lifetimes were discussed in an astrophysical context. High-resolution measurements on γ rays and protons would enable refinement of the PXCT by introducing the possibility of selecting the initial proton-emitting state and the excited final state. We have built a PXCT apparatus to extend this technique to constrain the lifetimes of resonances of interest for astrophysics.

2. Scientific Motivations

2.1. Application for rp -process

Type I X-ray bursts (XRBs) are the most frequent type of thermonuclear stellar explosions in the Galaxy. They are powered by thermonuclear runaways in hydrogen- and/or helium-rich material accreted onto the surface of a neutron star in a low-mass X-ray binary system. The main nuclear reaction flow in the XRB is driven toward the proton drip-line and to

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high masses via the αp -process (a sequence of (α, p) and (p, γ) reactions) and the rp -process (a series of rapid proton-captures and β^+ -decays). Accurate nuclear physics inputs such as β decay rates, masses, and nuclear reaction rates of neutron-deficient rare isotopes along the path of the αp - and the rp -process are needed to model the energy production and nucleosynthesis in XRBs. Our understanding of XRBs has greatly expanded while they still hold many open questions despite decades of work [10, 11, 12].

In a recent investigation to identify important reaction rates that affect XRB observables and nucleosynthesis, the $^{59}\text{Cu}(p, \gamma)^{60}\text{Zn}$ and $^{59}\text{Cu}(p, \alpha)^{56}\text{Ni}$ reaction rates were predicted to have significant impacts on the modeling of X-ray burst light curves and the composition of the burst ashes [13]. Under XRB conditions, the reaction flux beyond ^{56}Ni is affected by several cycles. As indicated in Fig. 2, a low $^{59}\text{Cu}(p, \gamma)^{60}\text{Zn}$ or a high $^{59}\text{Cu}(p, \alpha)^{56}\text{Ni}$ rate leads to the formation of a stronger NiCu cycle that strongly limits the synthesis of heavier nuclei and also affects the light curves [14]. Proton-capture onto ^{59}Cu either returns the cycle to ^{56}Ni or breaks out via $^{59}\text{Cu}(p, \gamma)$, depending on the $(p, \gamma)/(p, \alpha)$ rate ratio. The critical quantity determining the strength of the NiCu cycle is the ratio of the (p, α) to (p, γ) reaction rates at ^{59}Cu .

For a narrow isolated resonance, the resonant reaction rate can be calculated using the well-known relation [15],

$$N_A \langle \sigma v \rangle_r = 1.5394 \times 10^{11} (\mu T_9)^{-3/2} \times \omega \gamma \exp\left(-\frac{11.605 E_r}{T_9}\right) (\text{cm}^3 \text{s}^{-1} \text{mol}^{-1}), \quad (2)$$

where $\mu = A_T/(A_p + A_T)$ is the reduced mass in atomic mass units, with $A_p = 1$ and $A_T = 59$ as the mass numbers of proton and ^{59}Cu , respectively. E_r is the resonance energy in the center-of-mass system in units of MeV. T_9 is the temperature in units of giga kelvin (GK), and $\omega \gamma$ is the resonance strength in units of MeV, which is defined as:

$$\omega \gamma = \frac{2J_r + 1}{(2J_p + 1)(2J_T + 1)} \frac{\Gamma_p \times \Gamma_\gamma}{\Gamma_{\text{tot}}}, \quad (3)$$

where J_r is the spin of the resonance, $J_p = 1/2$ is the spin of proton, and $J_T = 3/2^-$ is the spin of the ground state of ^{59}Cu . The total decay width Γ_{tot} of the resonance is the sum of its partial decay widths, i.e., proton width (Γ_p), γ width (Γ_γ), and α width (Γ_α) since they represent the three open decay channels for the resonances of relevance to the thermonuclear $^{59}\text{Cu}(p, \gamma)^{60}\text{Zn}$ reaction rate. Alternatively, the resonance strength can be constructed by combining the level lifetime τ and the proton branching ratio $B_p = \Gamma_p/\Gamma_{\text{tot}}$ using the following expression:

$$\omega \gamma = \frac{2J_r + 1}{(2J_p + 1)(2J_T + 1)} B_p B_\gamma \frac{\hbar}{\tau}, \quad (4)$$

which are also applicable to the $^{59}\text{Cu}(p, \alpha)^{56}\text{Ni}$ reaction by replacing the γ terms with α terms ($J_\alpha = 0$). Therefore, measurements of the proton, γ -ray, and α -decay branching

ratios, and the lifetimes of the ^{60}Zn resonances within the Gamow window will suffice to determine the contribution of resonant charged-particle capture to the total reaction rates. Usually, we could use two techniques, β decay spectroscopy and the Doppler-shift attenuation method, and therefore, two separate experiments to measure branching ratios and lifetimes and constrain thermonuclear rates. Applying the PXCT based on EC is well suited to measure both in a single experiment.

The Gamow energies and windows for the $^{59}\text{Cu}(p, \gamma)^{60}\text{Zn}$ and $^{59}\text{Cu}(p, \alpha)^{56}\text{Ni}$ reactions shown in Table 1 are calculated from a numerical study of the relevant energy ranges for astrophysical reaction rates [16]. It can be seen that at any given temperatures below 2 GK, the corresponding effective energy windows will not exceed 2.8 MeV. Combined with the proton-separation energy of ^{60}Zn $S_p(^{60}\text{Zn}) = 5105.0(4)$ keV and α -separation energy of ^{60}Zn $S_\alpha(^{60}\text{Zn}) = 2691.7(5)$ keV, the excitation energy of interest should be from 5.1 to 7.9 MeV. Therefore, the key resonances in ^{60}Zn are energetically accessible in the β decay of ^{60}Ga owing to the large $Q_{\text{EC}}(^{60}\text{Ga}) = 14580(200)$ keV. In a recent $^{58}\text{Ni}(^3\text{He}, n)^{60}\text{Zn}$ reaction measurement [17], the nuclear level density of ^{60}Zn was extracted from the neutron evaporation spectrum. For the excitation energies at 6 MeV, the level density is estimated to be only $\sim 18 \text{ MeV}^{-1}$. The β decay of the 2^+ ground state of ^{60}Ga preferentially populates $J^\pi = 1^+, 2^+$, and 3^+ states in ^{60}Zn according to the β -decay selection rules. As the $\ell = 1$ proton captures on the $3/2^-$ ^{59}Cu ground state populate ^{60}Zn $0^+, 1^+, 2^+$, and 3^+ resonances, indicating an even lower level density for the states selected by β decay. All the ^{60}Zn states populated by allowed transitions are positive parity states, whereas the $\ell = 0, 2$ proton captures require a parity change. It is therefore not necessary to consider this scenario. Based on the analyses above, it is expected to obtain the properties of the ^{60}Zn resonances by identifying the discrete states populated in the β -decay of ^{60}Ga (see Fig. 3).

To narrow down the important resonances, we performed shell-model calculations using the NuShellX@MSU code [18] in the full fp -shell model space with the GPF1A interaction [19]. The properties of 72 ^{60}Zn states within excitation energies of 5 – 6.5 MeV are calculated and used as input to determine the resonant capture component of the $^{59}\text{Cu}(p, \gamma)^{60}\text{Zn}$ reaction rate. As shown in Table 2, the resonant capture contributions from four resonances are found to be dominant over a temperature range. A quenching factor $q^2 = 0.6$ for the matrix elements of the Gamow-Teller operator was used to calculate the β -feeding intensities in the ^{60}Ga decay. It can be seen that at least one of the four key resonances can be populated with a large decay branching ratio, and thus a lower limit on the $^{59}\text{Cu}(p, \gamma)^{60}\text{Zn}$ reaction rate would be set. A strong lower limit on the $^{59}\text{Cu}(p, \gamma)^{60}\text{Zn}$ reaction rate would indicate very weak NiCu cycling and therefore solve the astrophysical problem.

Even if the level density is still too high to distinguish discrete resonances, we can derive the particle and γ -transmission coefficients, which are essential ingredients to calculate the reaction rates with the statistical model [20]. Calculations in the statistical model require the input of a

Table 1: Gamow windows $\bar{E}_{\text{hi}} - \bar{\Delta} \leq E \leq \bar{E}_{\text{hi}}$ and Gamow peaks \bar{E}_0 for the $^{59}\text{Cu}(p, \gamma)^{60}\text{Zn}$ and $^{59}\text{Cu}(p, \alpha)^{56}\text{Ni}$ reactions at a temperature T .

T (GK)	$^{59}\text{Cu}(p, \gamma)^{60}\text{Zn}$			$^{59}\text{Cu}(p, \alpha)^{56}\text{Ni}$		
	$\bar{E}_{\text{hi}} - \bar{\Delta}$ (MeV)	\bar{E}_{hi} (MeV)	\bar{E}_0 (MeV)	$\bar{E}_{\text{hi}} - \bar{\Delta}$ (MeV)	\bar{E}_{hi} (MeV)	\bar{E}_0 (MeV)
0.5	0.51	0.92	0.71	0.55	0.98	0.74
1.0	0.67	1.26	0.91	0.73	1.48	1.01
1.5	0.75	1.57	1.01	0.87	2.11	1.27
2.0	0.82	1.83	1.14	1.01	2.80	1.74

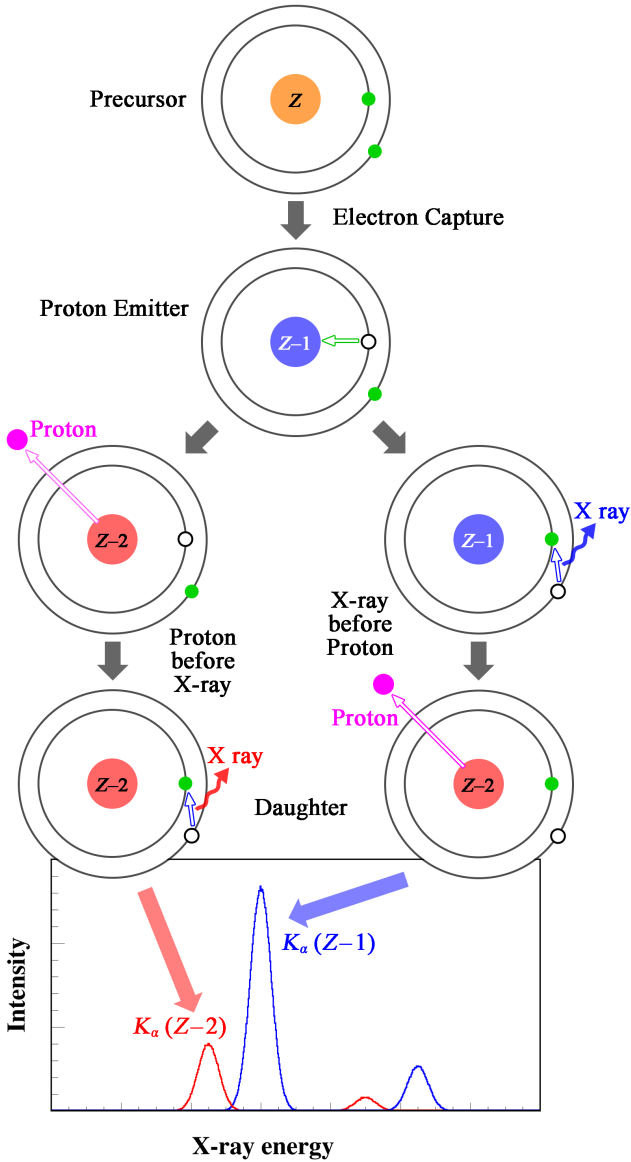


Figure 1: Cartoon illustrating the proton-X-ray coincidence technique. See text for details.

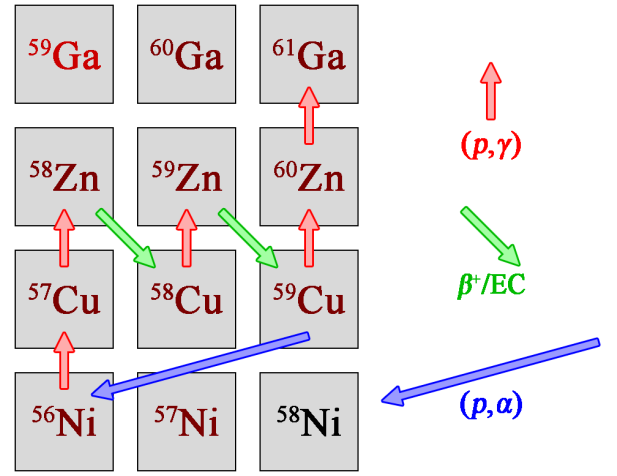


Figure 2: Portion of the rp -process reaction sequence featuring the NiCu reaction cycle.

Table 2: Properties of the dominant resonances in the $^{59}\text{Cu}(p, \gamma)^{60}\text{Zn}$ reaction. The values listed in the first through fifth columns are the dominating region of temperature, spin and parity (J^π), excitation energy (E^*), resonance energy (E_r), and β -feeding intensity (I_β) of each resonance, respectively.

T (GK)	J^π	E^* (keV)	E_r (keV)	I_β (%)
0.10 – 0.15	3^+	5362	257	0.05
0.15 – 0.45	1^+	5568	463	3.75
0.45 – 0.70	2^+	5648	543	0.15
0.70 – 7.50	2^+	6079	974	0.39

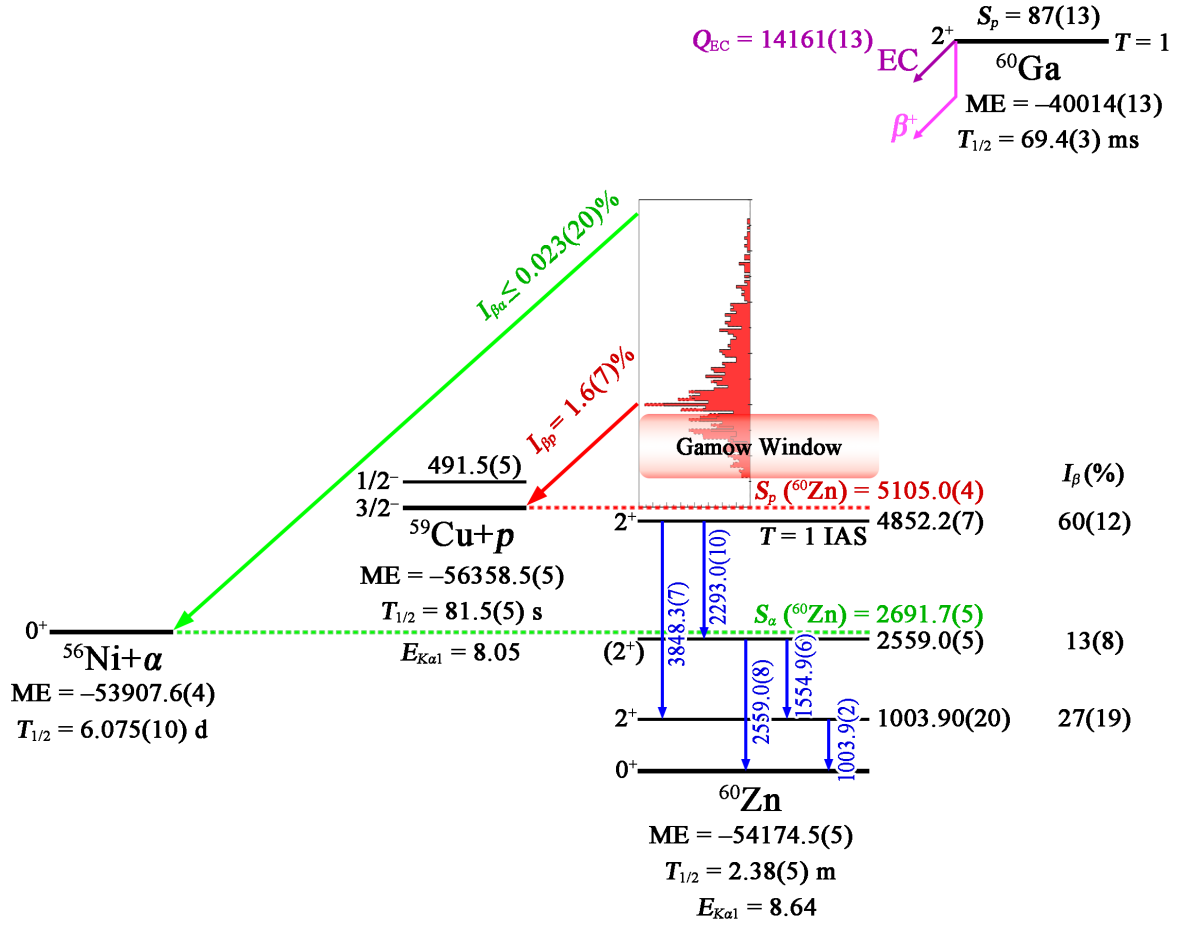


Figure 3: Previously established decay scheme of ^{60}Ga . All energies labeled in the scheme are given in units of keV. The mass excesses of ^{56}Ni , ^{59}Cu , and ^{60}Zn are from AME2020 [25]. The mass excess of ^{60}Ga is the weighted average of values reported by Refs. [26, 27]. The proton-separation energy and the β -decay Q -value of ^{60}Ga are obtained using this average mass. The spins, parities, and excitation energies are from the evaluation [28]. The γ -ray energies, β -feeding intensities, and the proton spectrum are from ^{60}Ga β spectroscopy of [29]. The half-life of ^{60}Ga is the weighted average of values reported by Refs. [26, 29, 30, 31].

number of different statistical properties. The standard approach in the calculation of reaction rates for astrophysics in a Hauser-Feshbach statistical model is to include a number of discrete excited states when experimentally known. The important ingredients of statistical model calculations are the particle and γ -transmission coefficients T and the level density of excited states ρ . Currently, experimental information on the $^{59}\text{Cu}(p, \gamma)^{60}\text{Zn}$ and $^{59}\text{Cu}(p, \alpha)^{56}\text{Ni}$ reactions is scarce. A direct cross section measurement of the $^{59}\text{Cu}(p, \alpha)^{56}\text{Ni}$ reaction at energies far higher than the Gamow window for X-ray bursts was found to be lower than statistical model calculations [21]. The PXCT approach has wide applicability to constrain other reaction rates of particular importance in the rp -process. As ^{64}Ge plays an analogous role in the ZnGa cycle to the role of ^{60}Zn in the NiCu cycle, it is desirable to extend this method to study the β -decay of ^{64}As in the future.

2.2. Application for p -process

About 30–35 proton-rich nuclei, ranging from ^{74}Se to ^{196}Hg , the so-called p nuclei, cannot be produced by the s and r processes via neutron-capture reactions. The astrophysical origins of these nuclei are not yet fully understood. To date, the favored process for the production of p -nuclei has been the γ -process occurring in Type II Supernovae when the shock-front passes through the O- and Ne-rich layer of the star where temperatures are between $1.8 < T_9 < 3.3$ [22]. Currently, the γ -process nucleosynthesis calculations are mostly based on theoretical calculations of cross sections using the Hauser-Feshbach statistical model [32]. The nuclear statistical parameters that are required in such calculations are optical model potential, γ -ray strength functions, and nuclear level densities [23]. PXCT can also be applied to measure individual resonance strengths or to constrain the transmission coefficients of both the entrance and exit channels for statistical model calculations of thermonuclear rates.

Rauscher *et al.* performed a comprehensive, large-scale Monte Carlo study of nucleosynthesis in the γ process [33]. $^{110}\text{Sn}(\gamma, p)^{109}\text{In}$ is identified as one of the key rates determining the production uncertainties of p -nuclei ^{96}Ru and $^{106,108}\text{Cd}$ in the 15- and 25- M_{\odot} KEPLER model. Rapp *et al.* investigated the reaction flux patterns of the p -process using a multimass zone Type II SN shock-front model [34]. The $^{110}\text{Sn}(\gamma, p)^{109}\text{In}$ and $^{110}\text{Sn}(\gamma, \alpha)^{106}\text{Cd}$ reactions are both identified as particularly important (Fig. 4). PXCT can be used to measure lifetimes and branching ratios of unbound ^{110}Sn states for proton, α , and γ emission by the EC decay of ^{110}Sb to ^{110}Sn , which can then decay by proton or α emission to ^{109}In and ^{106}Cd , respectively (Fig. 5). This will provide insights into the competition between the $^{110}\text{Sn}(\gamma, p)^{109}\text{In}$ and $^{110}\text{Sn}(\gamma, \alpha)^{106}\text{Cd}$ reactions in the astrophysical γ process.

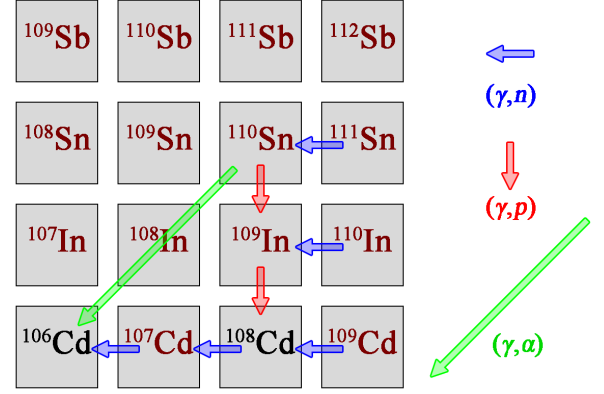


Figure 4: Portion of the rp -process reaction sequence featuring the NiCu reaction cycle.

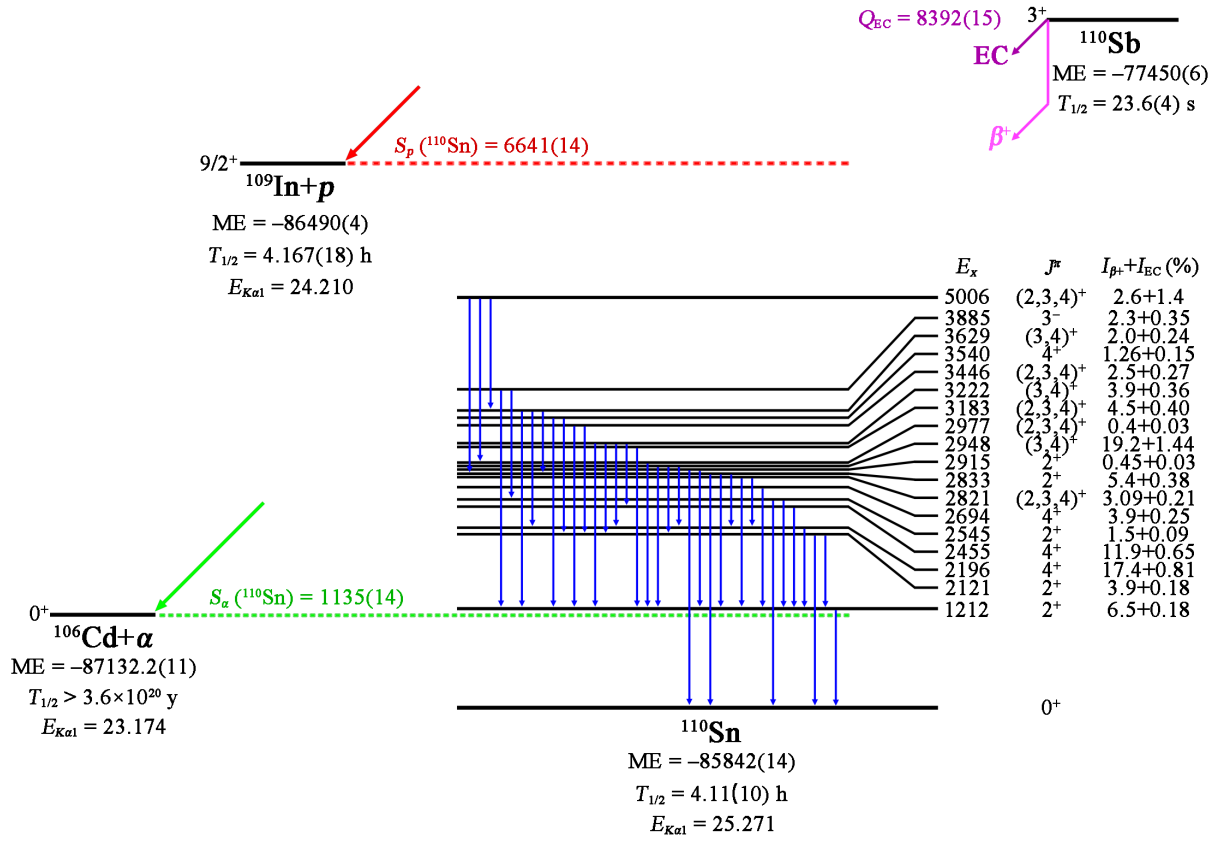


Figure 5: Previously established decay scheme of ^{110}Sb . All energies labeled in the scheme are given in units of keV. The mass excesses, the particle-separation energy, or the β -decay Q -value of ^{106}Cd , ^{109}In , ^{110}Sn , and ^{110}Sb are from AME2020 [25]. The spins, parities, excitation energies, and β -feeding intensities of ^{110}Sn states are from the evaluation [35]. The half-life of ^{110}Sb is the weighted average of values reported by Refs. [36, 37, 38].

3. Experimental Setup

We have built a PXCT detection system at the Facility for Rare Isotope Beams, where a sufficient intensity of a stopped ^{60}Ga beam will enable the application of this technique to study the ^{60}Zn resonances populated in the EC decay of ^{60}Ga [29]. The mechanical design of the PXCT apparatus is presented in Fig. 6. The beam is implanted into a thin collection foil at the center of a vacuum chamber. The detection system comprises a ΔE - E silicon detector telescope for charged-particle detection, two large-volume coaxial germanium detectors for γ -ray detection, and a planar germanium detector for X-ray detection. To mitigate the attenuation of X-rays, we employ thermalized beams because of their shorter implantation depths compared with fast beams.

We have selected two circular Si detectors, MSD012 of 12 μm thickness [39] and MSD026 of 1000 μm thickness [40] manufactured by Micron Semiconductor Ltd to construct a ΔE - E telescope. The numbers following MSD indicate the active area diameter in millimeters. The dead layer window and metallization type for MSD012 are 9.5P/7P, and for MSD026 are 9.5P/2M. Here, 9.5 represents a dead layer with a thickness of 50 nm, 7 represents a dead layer with a thickness of 300 nm, and 2 represents a dead layer with a thickness of 500 nm. P denotes a periphery metal band with a width of 30 μm around the edge of the active areas and contact pads for wire bonding and the majority of the active area does not have metal coverage. M denotes a continuous metal coverage with a thickness of 500 nm over the entire active area region. Both silicon chips are assembled onto an FR4 printed circuit board.

We have selected a Mirion Low Energy Germanium Detector (LEGe) model GL0510 (S/N:13725) for X-ray detection [41]. The LEGe detector consists of a Ge crystal with a diameter of 25.0 mm and a length of 10.5 mm. LEGe is housed in a cryostat with a diameter of 38.1 mm and a 0.13-mm thick beryllium entrance window, ideally suited for X-ray spectroscopy from 3 keV up. LEGe is fabricated with a thin contact on the front face and a rear contact that covers less than the full area, resulting in lower capacitance compared to a planar device of similar size. Since preamplifier noise is a function of detector capacitance, LEGe features low noise and high resolution at low and moderate energies.

We have selected two Mirion Extended Range Coaxial Germanium Detectors (XtRa) model GX10020 for γ -ray detection [42]. The active region of XtRa1 (S/N:5593) has a diameter of 84.8 mm and a thickness of 65.2 mm, while XtRa2 (S/N:5596) has a diameter of 79.8 mm and a thickness of 80.0 mm. Conventional coaxial detectors have a lithium-diffused contact typically of 0.5 to 1.5 mm thickness, which forms a dead layer that stops most photons below 40 keV, rendering the detector virtually inefficient at low energies. However, the XtRa detectors, feature an exclusive thin window contact on the front surface and a 0.6-mm-thick carbon composite cryostat window, which enables a good low-energy response.

All three Ge detectors are equipped with the Cryo-Pulse 5 Plus (CP5-Plus) electrically refrigerated cryostat. A 5-watt

pulse tube cooler is integrated into a compact coldhead-assembly, which is directly attached to the detector housing. CP5-Plus features low vibration, low noise, low power demand, and a maintenance-free operation [43]. The assembly is connected to a bench-top power controller that provides the required output voltage to drive the compressor. The controller also contains the necessary logic to ensure the safe and reliable operation of the cryostat. An RS-232 serial interface and CP 5-Plus control panel application are also included, allowing for remote monitoring of the cooler status.

All three Ge detectors are equipped with the Intelligent Preamplifier (iPA) [44], which incorporates a low-noise field-effect transistor (FET) input circuit optimized for the ultra-high source impedance of germanium detectors. The first stage of iPA serves as an integrator providing an output voltage proportional to the accumulated charge from the detector, and also functions as an electrometer for measuring the leakage current of the detector. The second stage acts as an output buffer and allows for four conversion factors of 50, 100, 250, and 500 mV/MeV. The iPA generates an inverted output signal that is split into two outputs, each with a termination impedance of 93 and 50 Ω . Additionally, the iPA is equipped with a warm-up sensor that is thermally connected to the detector. A USB interface and a control panel application provide real-time monitoring of detector current, temperatures, and preamplifier operating voltages. The four output gains as well as external or internal test pulsers are selectable via the control panel application.

Both the Ge detector and the coldhead are equipped with temperature sensors that serve as safety measures. In the event that the temperature exceeds the normal operating range, these sensors trigger the high-voltage inhibit signal from the preamplifier and the controller, respectively. This feature ensures the timely shutdown of the high-voltage bias supply, providing protection to the detector.

The output signals from all the preamplifiers are digitized by a 16-bit, 250 Mega samples per second Pixie-16 module manufactured by XIA LLC [45]. A general-purpose nuclear physics data acquisition system Digital Data Acquisition System (DDAS) is used [50, 51] for recording and processing data. Trapezoidal filtering algorithms are implemented in both the slow filter for pulse height measurement and the fast filter for leading-edge triggering. Each event is time-stamped using a constant-fraction discriminator (CFD) algorithm.

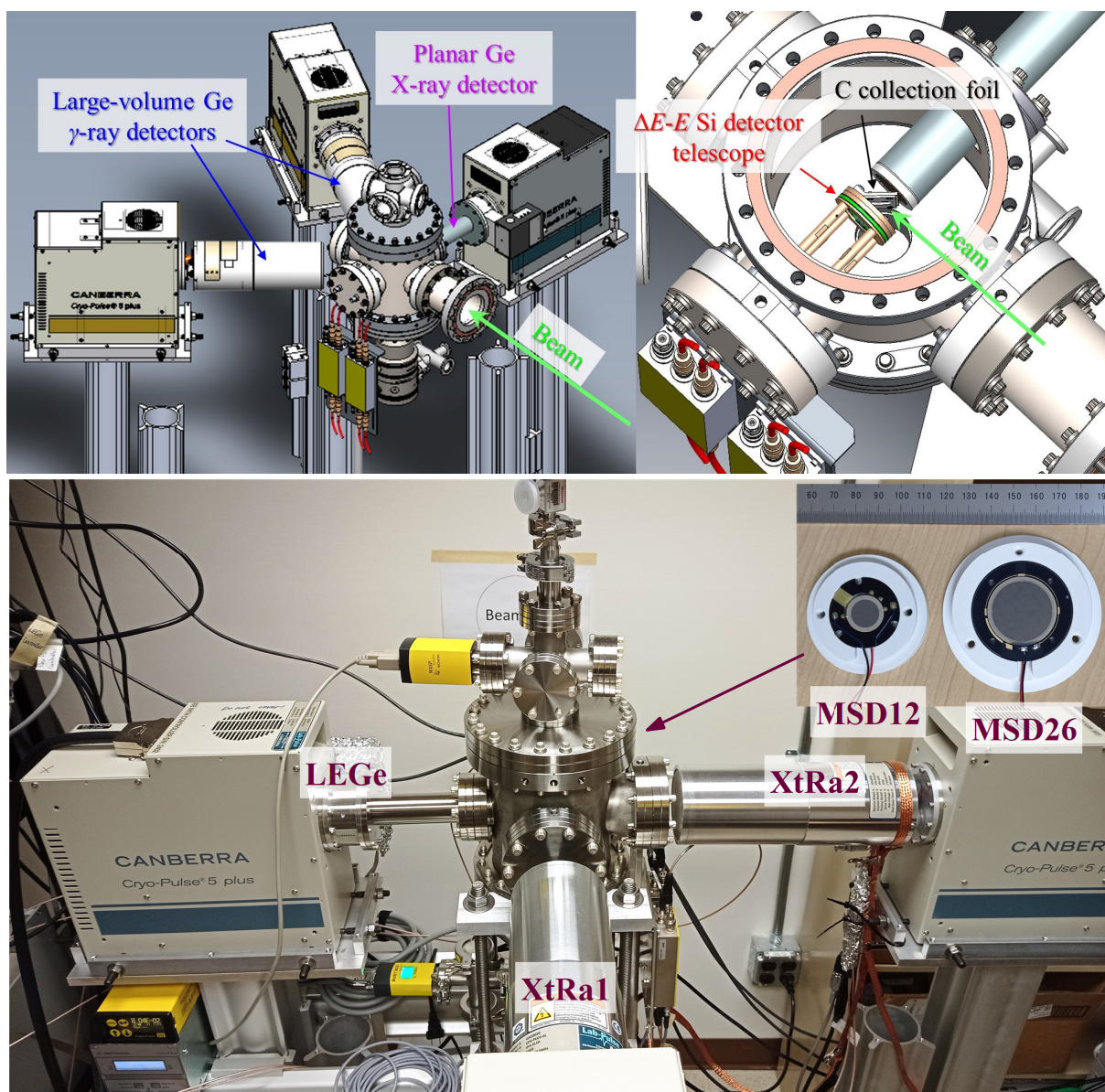


Figure 6: Mechanical design and photograph of the PXCT setup.

4. Test

One Mesytec MHV 4-channel bias supply module is used to provide the bias voltages to the two Si detectors. MHV offers 5 V ramp speed to protect the circuits of preamps. MSD12 has a depletion voltage of 1.5 V and is operated at 3.0 V, and MSD26 has a depletion voltage of 90 V and is operated at 130 V. We apply a negative bias to the p^+ contacts of both MSD detectors through the preamplifiers and ground the n^+ contacts. We choose Mesytec MPR-1 single-channel charge-sensitive preamplifiers. The leakage current for MSD26 ranges from 60 to 110 nA, whereas remains below 1 nA for MSD12. Two ORTEC 660 Dual Bias Supply modules provide the bias voltages to the three Ge detectors. LGe becomes fully depleted at a bias voltage of 600 V and is recommended to be operated at 1100 V. XtRa1 and XtRa2 become fully depleted at a bias voltage of +4000 V and +2200 V, respectively, and both are operated at 4500 V. We apply a negative bias to the p^+ contacts of LGe and a positive bias to the n^+ contacts of the XtRa detectors. ORTEC 660 includes a remote bias shutdown feature to protect the preamplifier FET against damage when a cooled Ge detector warms up. The typical leakage currents of the two XtRa detectors are below 20 pA and below 100 pA for LGe. The linear tail pulses from MPR-1 have nominal rise times of 500 ns for MSD12 and 70 ns for MSD26, respectively, and the decay time constant is 120 μ s for both.

The amplitude distribution recorded by the pulse analysis system is 0.13% (Pulser), 3.17% (MSD12), 0.84% (MSD26), 0.26% (XtRa1), and 0.24% (XtRa2), demonstrating the electronic noise level present in the system.

We have evaluated the performance of the LGe detector using X rays and low-energy γ rays from ^{55}Fe , ^{152}Eu , and ^{241}Am radioactive sources, as shown in Fig. 7. The energy resolution achieved by LGe is characterized by fitting 12 known X-ray or γ -ray lines with an exponentially modified Gaussian (EMG) function [46, 47] at 5.90 keV (Mn $K_{\alpha 1}$), 6.49 keV (Mn $K_{\beta 1}$), 11.89 keV (Np L_{ℓ}), 13.76 keV (Np $L_{\alpha 2}$), 13.95 keV (Np $L_{\alpha 1}$), 26.34 keV (^{237}Np γ), 33.20 keV (^{237}Np γ), 39.52 keV (Sm $K_{\alpha 2}$), 40.12 keV (Sm $K_{\alpha 1}$), 45.29 keV (Sm $K_{\beta 3}$), 45.41 keV (Sm $K_{\beta 1}$), and 59.54 keV (^{237}Np γ). At the energies of interest, 8.05 keV (Cu $K_{\alpha 1}$) and 8.64 keV (Zn $K_{\alpha 1}$), the full width at half maximum is estimated to be 238(8) and 241(7) eV, respectively, providing enough resolving power to distinguish the X rays from two nearby elements.

For low-energy photons, the photoelectric effect process is predominant, the photon is absorbed and its energy is transferred to an electron and causes the prompt emission of a characteristic X ray as the resulting vacancy in the electron shell is filled. In most cases, this X ray is reabsorbed near the original interaction site. However, most of the absorptions occur near the surface of the detector where the escape of the resulting X ray can be significant, resulting in peaks usually at 9.89 keV and 10.98 keV below the photopeaks, known as Ge escape peaks (Fig. 7). These energy differences correspond to the characteristic $K_{\alpha 1}$ and $K_{\beta 1}$ X-ray energies for Ge, respectively [52].

For photon energies just above the K-shell binding energy of

Ge, 11103.0 ± 2.0 eV, the incident photon is strongly absorbed without deep penetration beyond the detector surface. The subsequent characteristic K X ray tends to escape, decreasing the full energy peak efficiency. This effect occurs at the K-edge for Ge, which can potentially complicate the normalization of near-edge X rays. For our energy of interest, K-shell absorption is no longer possible and L-shell interactions predominate. In this case, the incident gamma ray tends to penetrate somewhat deeper and the energy of the fluorescent L X ray is much lower, leading to a diminished probability of escape.

Two factors limit the ultimate time resolution that can be achieved with germanium detectors. One is that the charge collection process is inherently slow. Even at the saturated drift velocity, the time required for a charge carrier to travel a distance of 1 cm (which may be of the order of the detector thickness) is approximately 100 ns. Typical pulse rise times will therefore be as large as several hundred nanoseconds. These times are much longer than the output from fast detectors (such as organic scintillators) and therefore the time performance can never be as good. A second factor, however, makes the timing properties even worse. As will be illustrated below, the detailed shape of the pulse rise from germanium detectors can change substantially from event to event, depending on the position at which the electron-hole pairs are created within the active volume. When the volume of the detector is uniformly irradiated, these positions are more or less randomly distributed, and therefore the output pulses show a great variation in the shape of their leading edge. Ideally, the rise time of the pulse produced from the preamplifier is determined only by the charge collection time in the detector and is independent of the capacitance of the detector or preamp input. The timing resolution is The coincidence between photons and charged particles can be constructed accordingly. The FWHM timing resolution of each detector measured using a pulse generator Canberra Model 1407P fed to each test of preamplifiers is 37.4 ns (MSD12), 4.4 ns (MSD26), 1.2 ns (XtRa1), 1.8 ns (XtRa2). The pulser itself has a resolution of 0.32 ns. while using radioactive sources is 44 ns.

The coincidences between each detector were studied using an ^{241}Am source placed at the center of the chamber and a ^{152}Eu source placed outside of the chamber (See Fig. 12). The sources were positioned in such a way that the α - γ coincidences could be detected by MSD ΔE - E and LGe, and γ - γ coincidences could be detected by LGe and two XtRa detectors.

In addition to the lifetimes obtained from the measured K_{α} X-ray intensities, the system also measures proton, γ -ray, and α -particle branching ratios (Γ_p/Γ , Γ_{γ}/Γ , Γ_{α}/Γ , respectively), ideally for discrete resonances for the first time. By gating on different protons and γ rays, we can extract the lifetime for a specific state. This method will also provide experimental information on the nuclear level density and transmission coefficients needed to calculate rates using the statistical model. Based on a complete set of data, the $^{59}\text{Cu}(p, \gamma)^{60}\text{Zn}$ and $^{59}\text{Cu}(p, \alpha)^{56}\text{Ni}$ reaction rates will be constrained. Hence, the proposed work has the potential to make a major step toward addressing the unknown strength of the NiCu cycle,

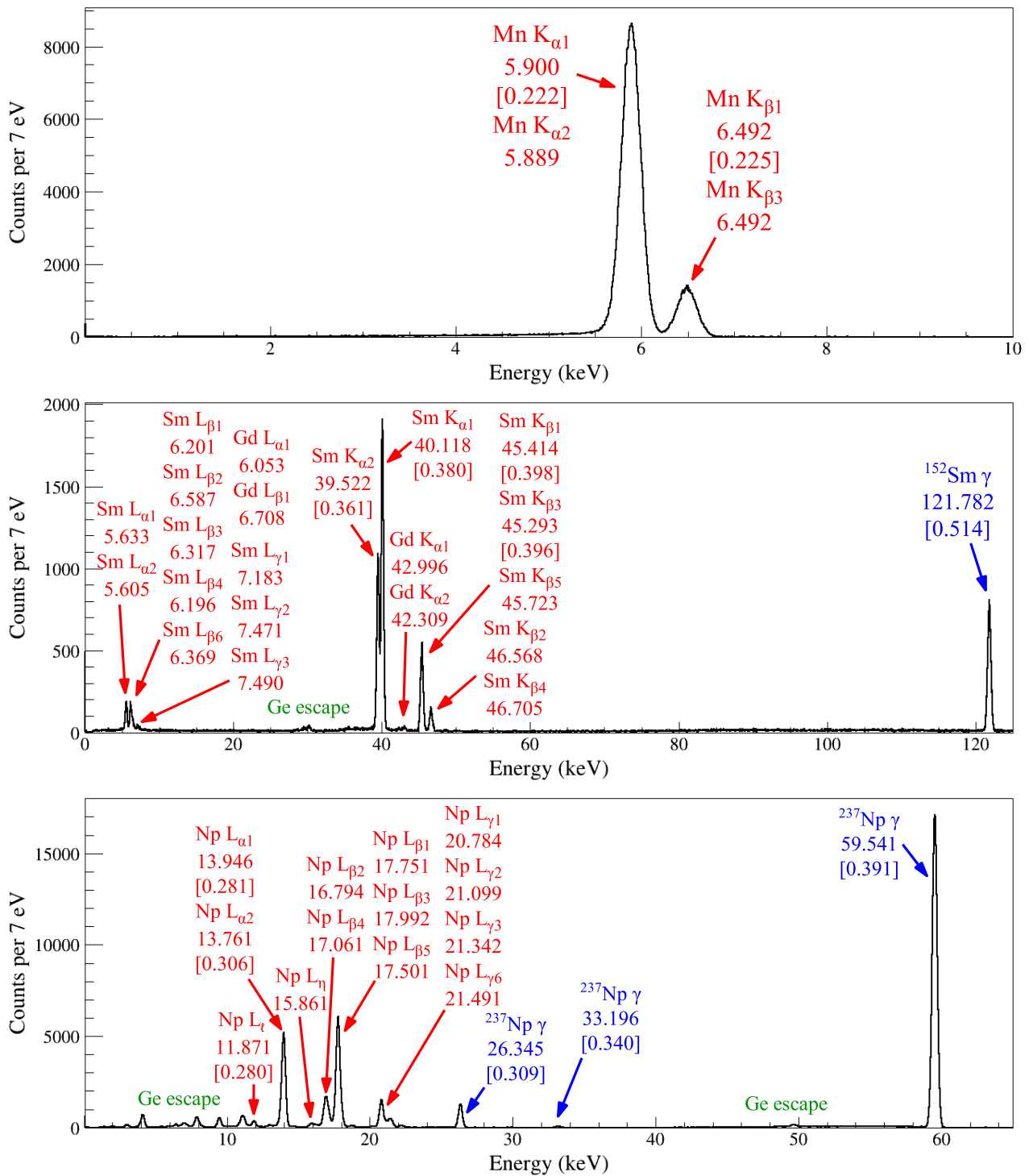


Figure 7: X-ray and/or γ -ray spectra measured by the LEGe detector using ^{55}Fe , ^{152}Eu , and ^{241}Am sources. All the X-ray and γ -ray energies are adopted from Ref. [52] in units of keV. The FWHM values used for the characterization of LEGe energy resolution are indicated within brackets.

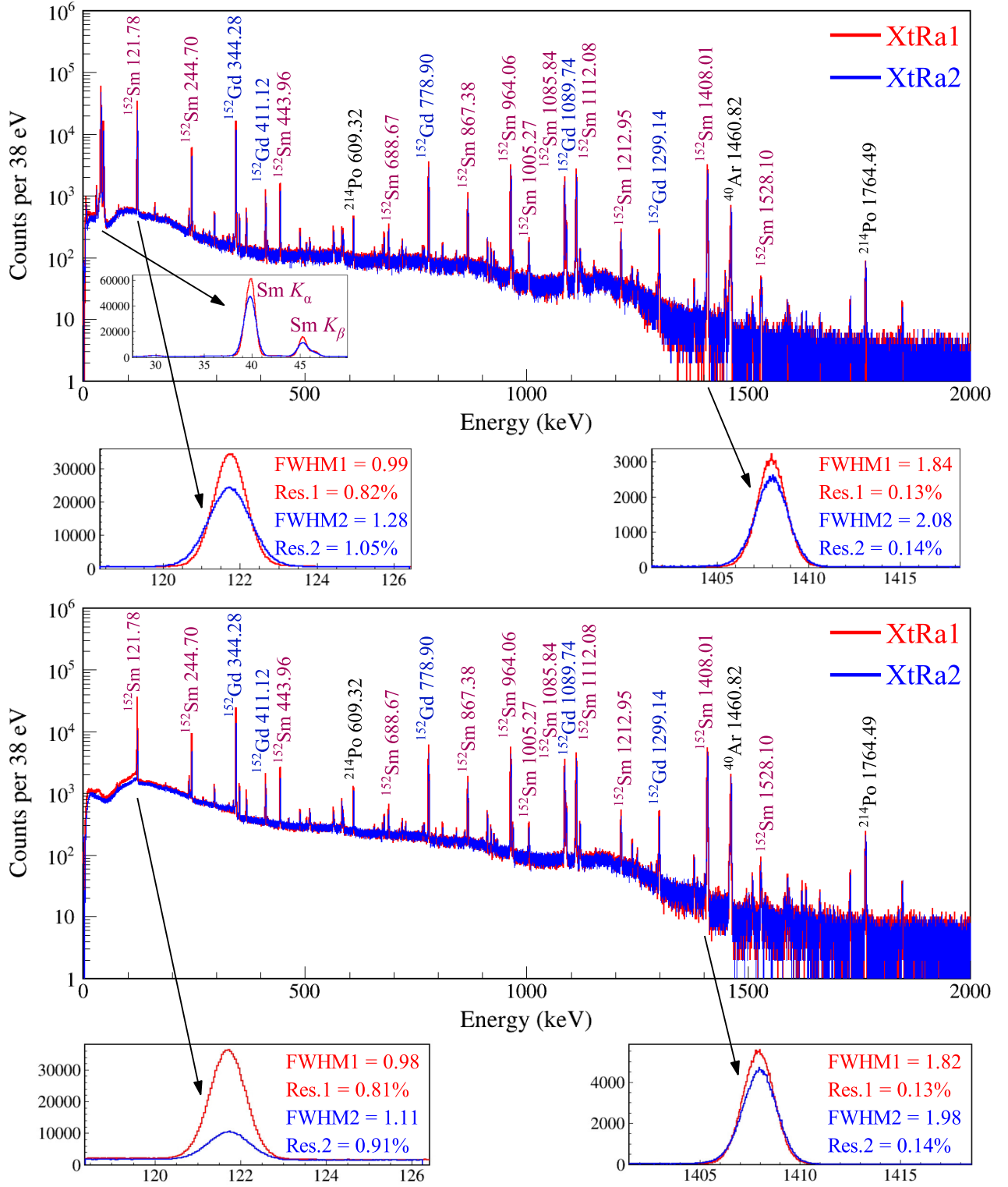


Figure 8: γ -ray spectra measured by XtRa1 (red) and XtRa2 (blue) using an ^{152}Eu source. Upper panel: ^{152}Eu source is placed at a distance of 14 cm from the detector window. Lower panel: ^{152}Eu source is placed at the center of the vacuum chamber. The insets show resolution at 122 keV and 1408 keV. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

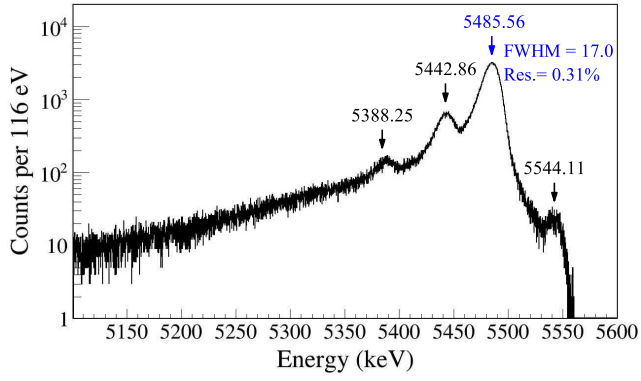


Figure 9: α spectrum measured by MSD26 using an ^{241}Am source. The α energy values are rounded to the nearest 0.01 keV.

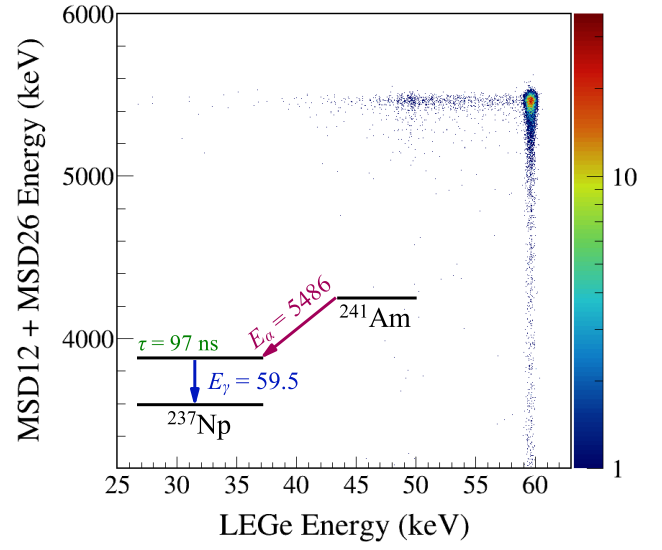


Figure 11: Coincidence spectrum between MSD detector telescope and LEGe obtained using an ^{241}Am source placed at the center of the chamber. A simplified ^{241}Am decay scheme shows the dominant α - γ coincidence.

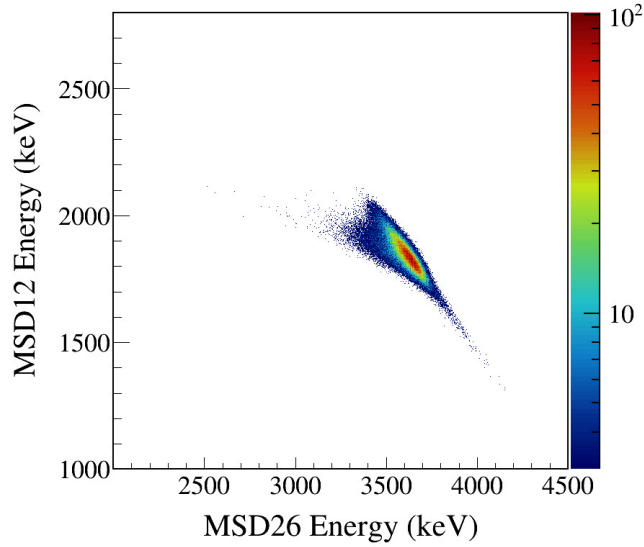
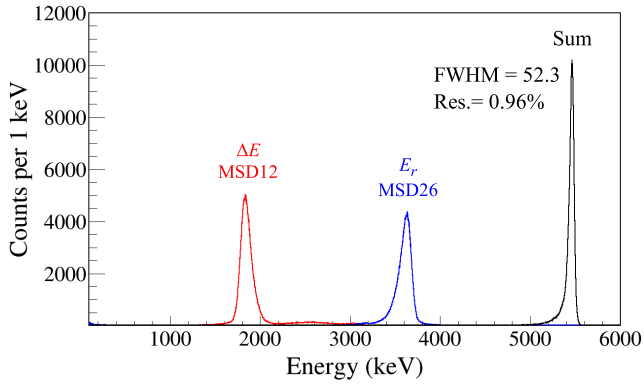


Figure 10: α spectrum measured by MSD12 and MSD26 using an ^{241}Am source. Upper: α -energy spectrum. Lower: ΔE - E 2D plot.

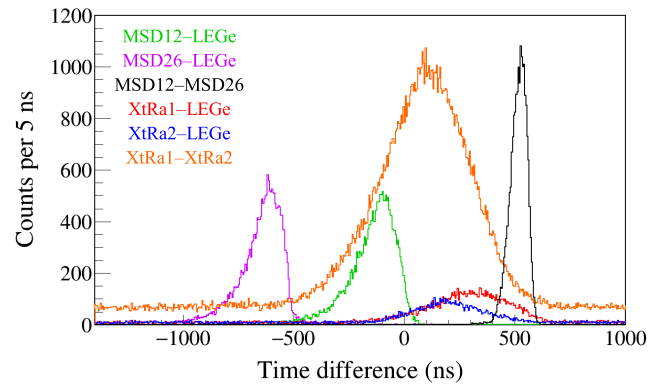


Figure 12: Coincidence time spectra between each detector obtained using an ^{241}Am source placed at the center of the chamber and a ^{152}Eu source placed outside of the chamber.

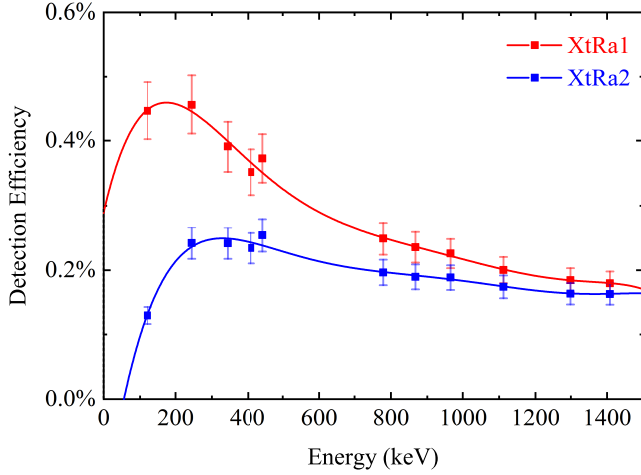


Figure 13: Absolute full-energy γ -ray detection efficiency of XtRa obtained using an ^{152}Eu source placed at the center of the chamber. The efficiency curves are simulated using GEANT4 (placeholder).

which is of critical importance for understanding the rp -process and the modeling of X-ray burst light curves.

The ^{60}Ga experiment cannot be run at TRIUMF-ISAC or CERN-ISOLDE because they cannot provide a ^{60}Ga beam of any intensity. The nearest isotope, ^{61}Ga , has only been produced at around 140 and 10 pps, respectively. FRIB will be the only facility in the world able to run the ^{60}Ga experiment in the foreseeable future. Considering a ^{60}Ga fast beam rate of 3.0×10^5 per second at FRIB, a week-long experiment would yield sufficient statistics using the built setup. To commission the PXCT setup in the D-line stopped-beam area of FRIB, we chose to reproduce the lifetimes obtained in the EC of ^{73}Kr (Fig. 14), one of the most well-studied cases by previous PXCT measurements [4, 6, 7] and decay spectroscopy [49]. Using the most recent version of LISE++ obtained from FRIB beam physicists including their “reality factor” yields a ^{73}Kr fast-beam intensity of 3.3×10^5 pps based on a ^{78}Kr primary beam incident upon a ^{12}C production target. Assuming an efficiency of 18.5% for extraction and delivery from the linear gas stopper based on the online FRIB beam-rate calculator yields 6.1×10^4 delivered to the implantation foil of the experimental setup. For an atom in an excited state, the ejection of an Auger electron is a competitive process to the emission of characteristic X rays. The fluorescent yield is defined as the fraction of all cases in which the excited atom emits a characteristic X-ray photon in its de-excitation.

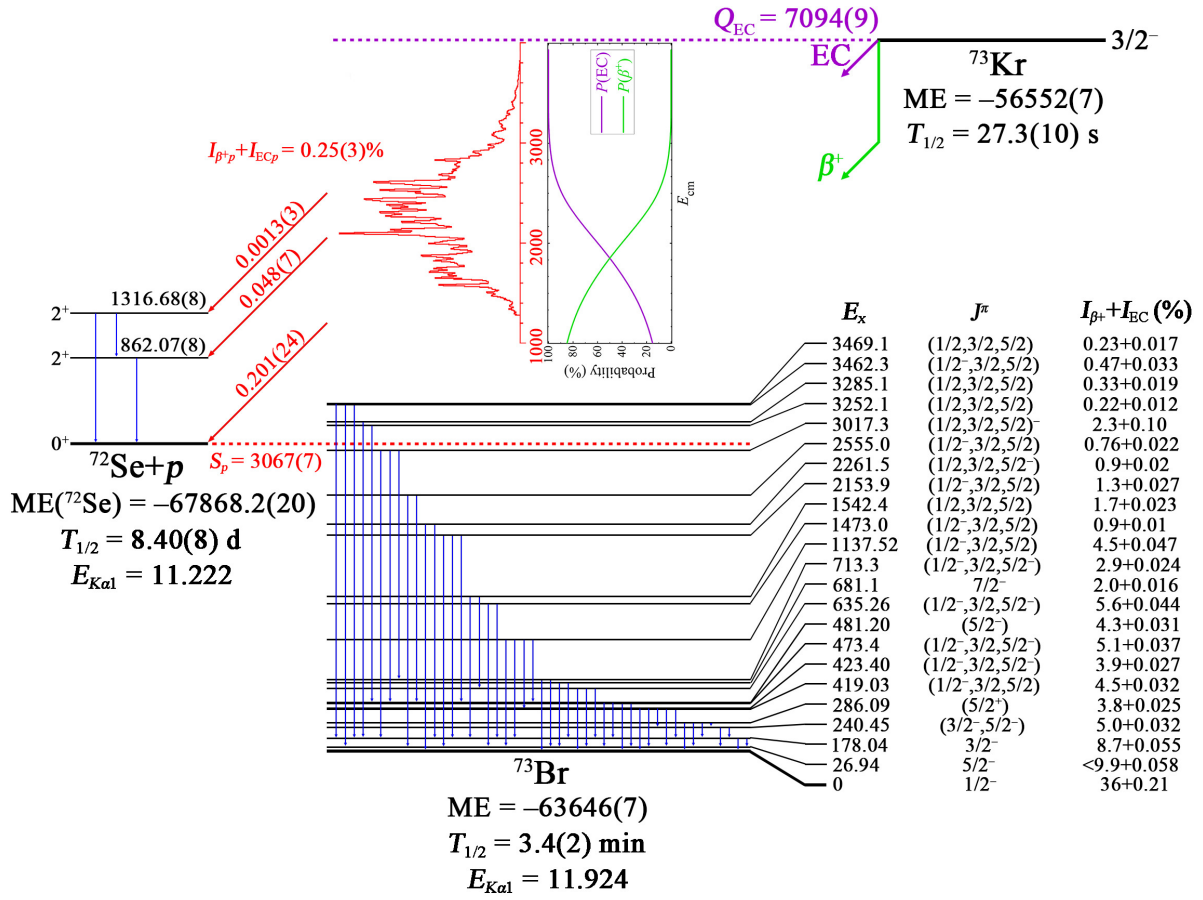


Figure 14: Previously established decay scheme of ^{73}Kr . All energies labeled in the scheme are given in units of keV. The mass excesses, the proton-separation energy, or the β -decay Q -value of ^{72}Se , ^{73}Br , and ^{73}Kr are from AME2020 [25]. All the half-lives and the spins, parities, excitation energies, and β -feeding intensities of ^{73}Br states are from the evaluation [48].

5. Summary

We aim to use a full-intensity ^{60}Ga FRIB beam to investigate ^{60}Zn resonances that determine the competition between the $^{59}\text{Cu}(p, \gamma)^{60}\text{Zn}$ and $^{59}\text{Cu}(p, \alpha)^{56}\text{Ni}$ reactions of the rp process in X-ray Bursts. This competition determines whether the so-called NiCu cycle is open or closed and therefore affects the shape of the observed light curve.

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